Elevation-dependent warming and its climatic drivers: A concerted field and modeling assessment for an alpine national park

Simon Zitzmann[1,2], Benjamin Fersch[1], Carsten Jahn[1], Harald Kunstmann[1,2]

1: Institute of Meteorology and Climate Research – Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
2: Institute of Geography, University of Augsburg, Augsburg, Germany

Universität Augsburg University

KIT-Campus Alpin
IMK-IFU: Atmospheric Environmental Research

KIT Karlsruhe Institute of Technology

1. Background

- Elevation-dependent warming (EDW): Global warming occurs at varying rates across different altitudes.
- Studies comparing adjacent in situ observations show tendency for an increased warming trend at higher elevations. On the regional level, the manifestation of EDW varies (Pepin et al., 2022).
- Contribution of individual drivers, particularly regarding surface energy balance, is not well understood and varies between regions.
- The Berchtesgaden National Park is an ideal location to study the drivers of EDW: It covers a steep elevation gradient (600-2700 m.a.s.l.) in a small area and provides a dense network of weather stations (Marke et al., 2013).

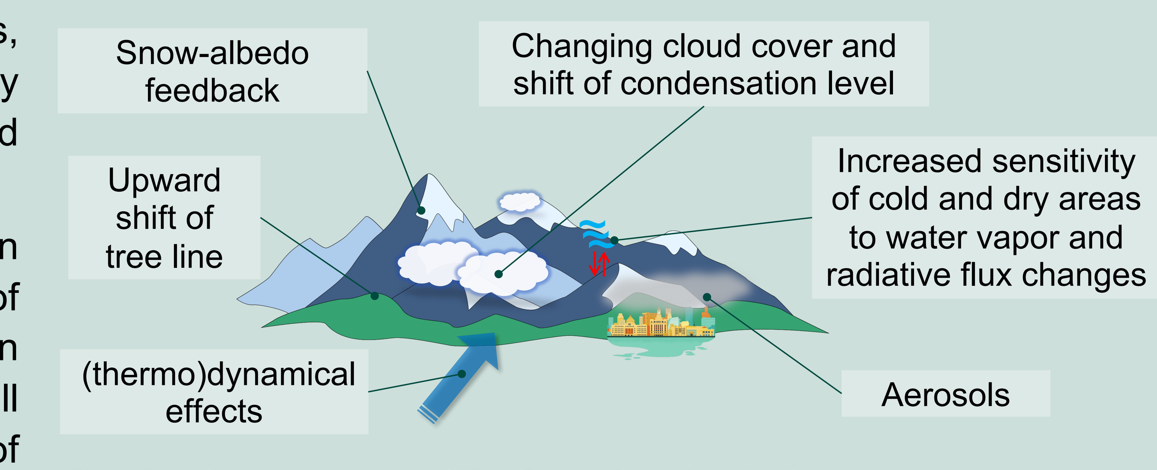

Fig. 1: Possible driving mechanisms of EDW (Pepin et al., 2015 and 2022).

2. Methods

Observational network of the national park

- The monitoring network currently comprises 19 stations.
- Automatic recording of 10-minute averages
- Measured variables:
  - All stations: Air temperature and humidity
  - Many: Wind speed and direction
  - Some: Radiation, precipitation, snow, ground temp.

Fig. 2: Weather station at Watzmannhaus.

Temporary observations of surface energy balance

- From 2023 to 2025, additionally installed meteorological stations measure the surface energy balance at three sites, covering 617 to 1930 m.a.s.l.
- They record the components of the net radiation and ground heat flux. The latter is monitored using heat flux plates buried in differently inclined slopes (north, east, south, west and not inclined).
- To determine the sensible and latent heat fluxes, the modified Bowen ratio method (Liu & Foken, 2001) is applied at the medium-altitude station Kühroint.

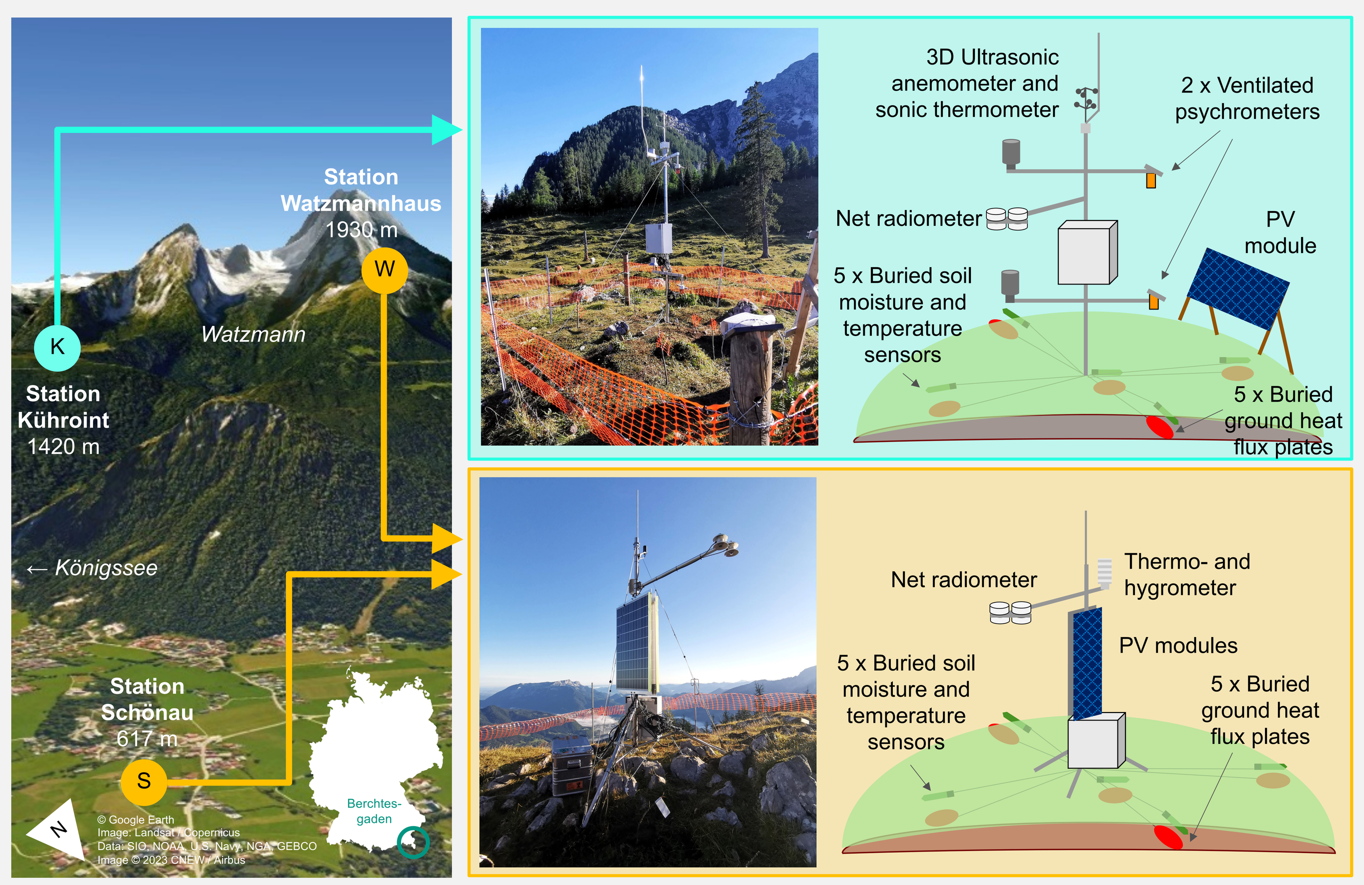

Fig. 3: Locations and equipment of the installed stations measuring the surface energy balance. Station Schönau and Watzmannhaus are equipped identically, except for the power supply, as there is a power connection in Schönau.

Modeling

- To identify the underlying mechanisms of EDW, the surface energy balance will be simulated with a land surface model at a high resolution of 100 m (Fersch et al., 2020) in the Berchtesgaden National Park.
- A past run and a run during the measurement period 2023-2025 will be performed, with the results validated against station data.
- A focus is set on the capability of the model to represent topographical effects such as slope inclination and shading to simulate the surface energy balance in complex terrain.

3. Results

Climate change in the German Alps

- According to HYRAS (Razafimaharo et al., 2020): warming in the German Alpine region within the last 70 years
- Local differences:
  - Garmisch-Partenkirchen: <1 K
  - Small regions with temperature increase >1.5 K

Temperature changes 1991-2020 vs. 1951-1980

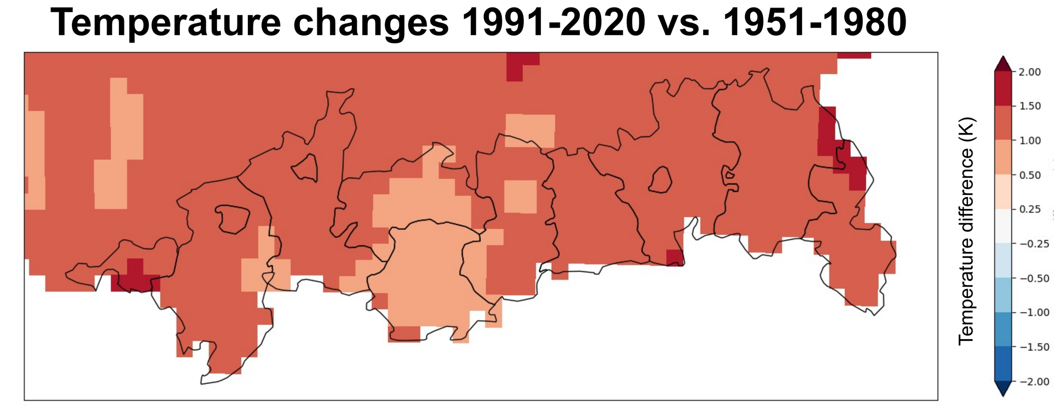

Fig. 4: Temperature changes in south-eastern Germany according to the gridded HYRAS data set. District boundaries are shown as black outlines.

Analysis of temperature observations in national park

- Comprehensive observations of weather data in the National Park exist since 2010 with minimal data gaps. Inclusion of DWD and Geosphere Austria station data in the analysis.
- Data quality checks were carried out using the Python package SaQC (Schäfer et al., 2023).
- Trend analysis of annual mean air temperature values with Mann-Kendall test (Kendall, 1948)

Temperature trends at different elevations and spatial patterns

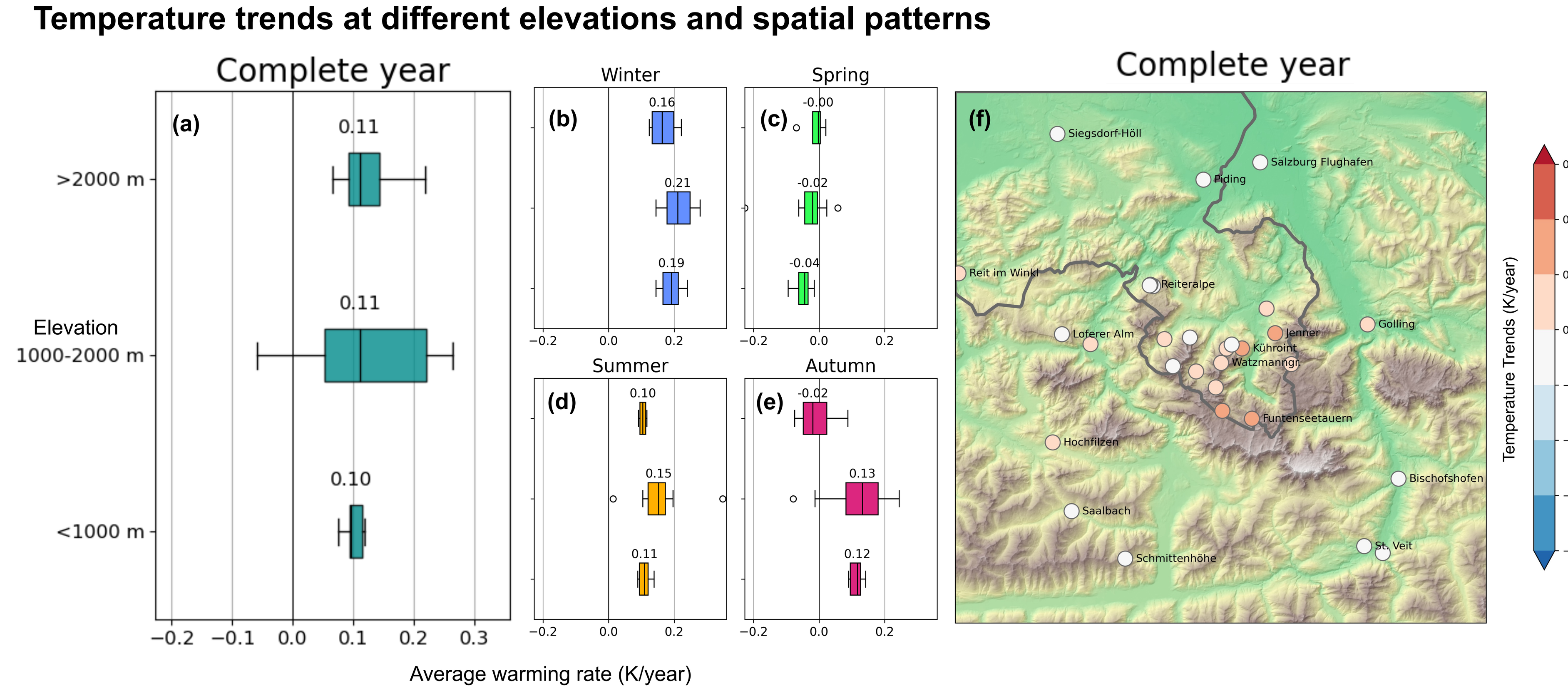

Fig. 5: a) - e): Box-whisker plots of temperature trends (annual mean temperatures and individual seasons, 2010-2023) of the stations in and around the national park for three elevation levels. f): Spatial distribution of annual mean temperature trends, relief and German-Austrian border in the background.

- Trends in annual mean temperatures (Fig. 5) are between 0.10 and 0.11 K/year on average for all elevation levels. More homogeneous trends at low altitude, heterogeneous trends at middle and high altitudes
- There are seasonal differences: In winter, summer and fall, the warming is enhanced at intermediate altitudes. In spring, the trend for the analyzed period is slightly negative at all altitude levels. In fall, the highest altitude level shows a slightly negative trend.
- Spatial examination of the trends shows some hotspots: Jenner, Kühroint and the southern part of the national park (around Funtenseetauern)
- For robust results, the analysis will be extended to longer time series and a larger area.

First investigation of surface energy fluxes at Kühroint

- Ground heat flux (averaged over all 5 sensors) and net radiation reach maximum at similar times
- Maximum of turbulent heat fluxes is later in the day
- Further post-processing of data and longer time series required
- Ground heat fluxes vary in amplitude and phase depending on the slope inclination: southern slope shows approx. 80 % higher maximum than northern slope

Surface energy fluxes at Kühroint (April 2-9, 2024)

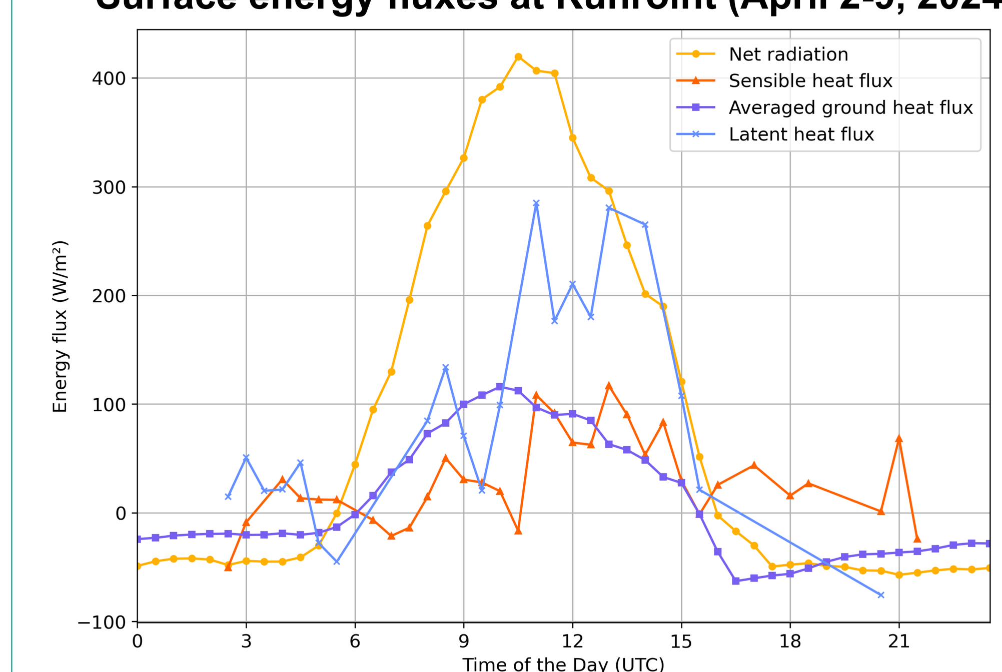

Fig. 6: Daily course of the surface energy fluxes at Kühroint, averaged over a week in April. The ground heat flux plotted is an average of all 5 sensors at the measurement site.

Ground heat fluxes (March 2024)

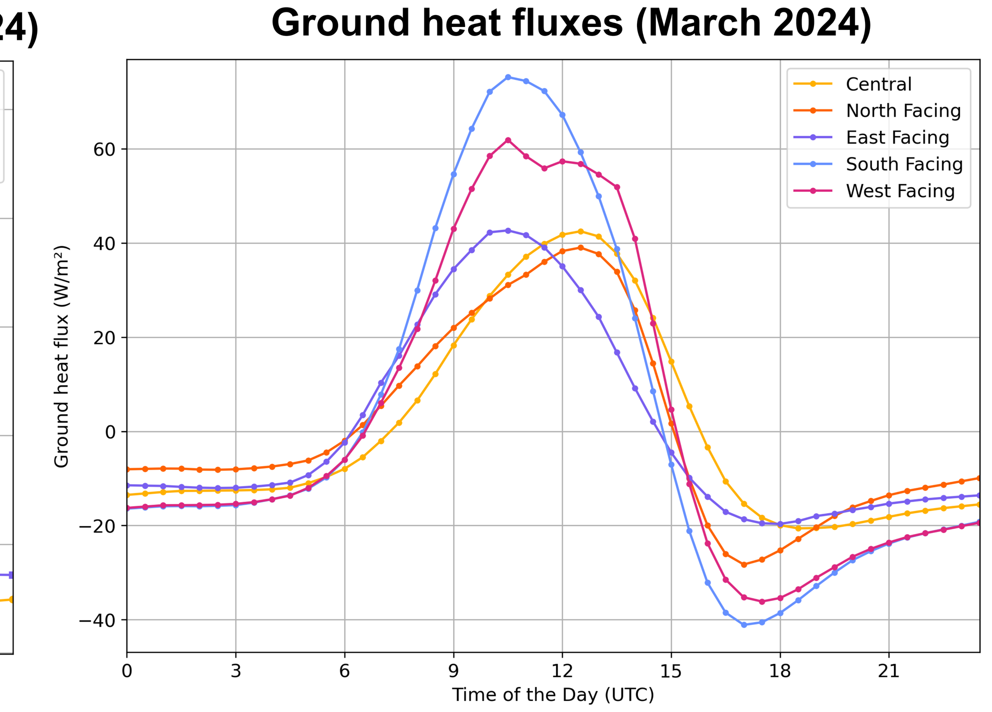

Fig. 7: Daily course of the ground heat fluxes at Kühroint, averaged over March 2024. The 5 sensors are buried at the same site in slopes facing different cardinal directions. The curves are slightly smoothed using a Savitzky-Golay filter.

4. Conclusion

- Elevation-dependent warming and microclimatic changes are investigated in the Berchtesgaden national park, Germany.
- Observational data set of the national park shows similar trends across altitude in the period 2010-2023 on average, but heterogeneous trends at higher elevations.
- In the individual seasons, enhanced warming is partly visible at middle and higher altitudes.
- Among other mechanisms (snow-albedo-feedback, changing cloud properties, etc.), investigation of ground heat flux is promising to understand microclimatic changes in mountain regions
- For a more profound understanding, surface energy fluxes are measured at three different altitude levels and a model of the national park area will be set up

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EGU Abstract

Contact

simon.zitzmann@kit.edu
linkedin.com/in/climate-simon

Project

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